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Design and Analysis of SPWM-Based Firing Pulse Modulation for Single-Phase Inverter Control

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ABSTRACT:
Sinusoidal Pulse Width Modulation (SPWM) is widely used in modern inverter systems to obtain high-quality AC output from a DC source. This paper presents the design and implementation of an SPWM-based firing pulse modulation scheme for a single-phase full-bridge inverter, with a focused investigation on how the modulation index influences the inverter's output voltage. The proposed system generates gate pulses by comparing a sinusoidal reference signal with a high-frequency triangular carrier, allowing precise control of switching instants. By varying the modulation index, the effective width of the pulses changes, which directly affects the RMS value of the output voltage. Experimental observations show a nearly linear relationship between modulation index and inverter output voltage within the linear modulation region, demonstrating the capability of SPWM to provide smooth and controllable voltage regulation while maintaining improved waveform quality. The study highlights how proper selection of modulation parameters can enhance inverter performance, reduce distortion, and offer a simple yet effective control approach suitable for educational platforms, low-power applications, and renewable energy interfaces

KEYWORDS: Sinusoidal Pulse Width Modulation (SPWM), Modulation Index, Single-Phase Inverter, PWM Control, Output Voltage Control, Harmonic Reduction, Power Electronics, DC-AC Conversion.

1. INTRODUCTION:

The need for efficient and dependable DC–AC power conversion has grown rapidly in recent years, especially with the expansion of renewable energy systems, uninterruptible power supplies (UPS), and variable-speed motor drives [1], [5], [10]. In all of these applications, inverters serve as a crucial link by converting DC power from sources such as batteries, solar panels or rectified supplies into usable AC power [2], [3]. Traditional inverters that generate square-wave or modified sine-wave outputs are simple and cost-effective, but they often produce high harmonic distortion and poor waveform quality [1], [4]. This can lead to overheating, reduced efficiency and unwanted stress on connected equipment, making them less suitable for sensitive or modern loads [2].

To address these issues, Pulse Width Modulation (PWM) techniques are commonly used in inverter control [4], [11]. Among them, Sinusoidal Pulse Width Modulation (SPWM) stands out because of its simplicity and its ability to produce an output waveform that closely resembles a pure sine wave [4], [6]. In SPWM, a low-frequency sinusoidal reference signal is continuously compared with a high-frequency triangular carrier signal to generate variable-width switching pulses [4]. These pulses are used to control the inverter's power switches, ensuring that the average output voltage follows the shape of a sine wave while significantly reducing low-order harmonics [2], [4].

A key parameter in SPWM operation is the modulation index, which directly influences the amplitude of the fundamental component of the inverter output voltage [4], [7]. By adjusting the modulation index, the RMS value of the output voltage can be smoothly controlled without modifying the DC input or changing the hardware design [2], [6]. This makes SPWM a highly flexible and practical method for voltage regulation in single-phase inverter systems.

In this work, an SPWM-based firing pulse generation scheme for a single-phase inverter is designed and implemented. The primary objective is to study how different values of the modulation index affect the inverter's output voltage. Through experimental observation and analysis, the paper aims to provide a clear understanding of voltage control using SPWM, making the study useful for academic learning as well as practical power electronics applications [6], [11].

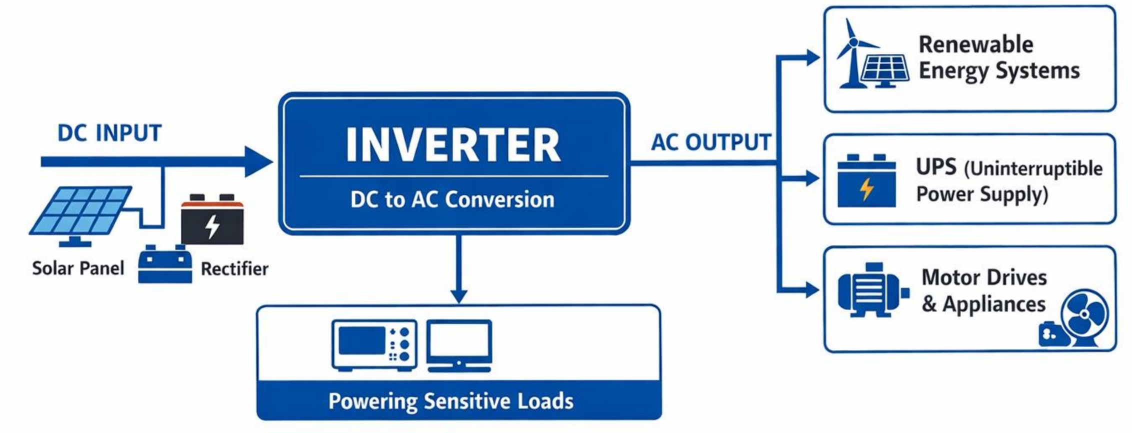

Fig. 1: Inverter application and power Conversion

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THEORY:

Principle of SPWM

Sinusoidal Pulse Width Modulation (SPWM) is a widely used technique for controlling inverter switches in order to generate a high-quality AC output from a DC source. The basic idea behind SPWM is simple yet powerful: instead of directly producing a square wave, the inverter switches are controlled in such a way that the average output voltage follows the shape of a sine wave.

The principle of SPWM is based on the comparison of two signals:

1. A low-frequency sinusoidal reference signal, which represents the desired AC output waveform (usually 50 Hz or 60 Hz).
2. A high-frequency triangular carrier signal, which determines the switching frequency of the inverter.

When the instantaneous value of the sine reference signal is greater than that of the triangular carrier signal, the upper switch of the inverter leg is turned ON. When the triangular signal becomes greater, the lower switch is turned ON. This continuous comparison produces a series of pulses whose widths vary according to the amplitude of the sine wave.

As the sine wave increases toward its peak, the generated pulses become wider. As it moves toward zero, the pulses become narrower. This variation in pulse width ensures that the average value of the inverter output voltage over each switching cycle closely follows a sinusoidal pattern. After passing through a filter, the high-frequency switching components are removed, leaving a smooth AC waveform.

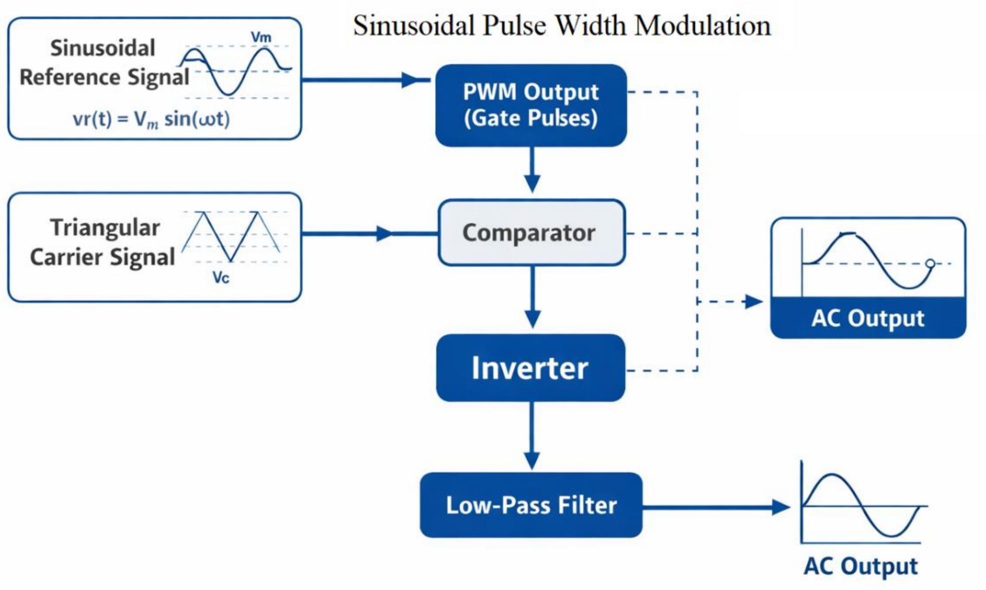

Fig.2 Sinusoidal PWM block diagram illustration

An important feature of SPWM is the modulation index, defined as the ratio of the amplitude of the sine reference signal to the amplitude of the triangular carrier signal. The modulation index directly controls the amplitude of the fundamental output voltage. Within the linear modulation range, increasing the modulation index increases the RMS output voltage proportionally.

By shifting most harmonic components to higher frequencies around the carrier frequency, SPWM makes filtering easier and significantly improves output waveform quality compared to square-wave inverters. Because of this balance between simplicity, controllability and performance, SPWM remains one of the most preferred modulation techniques in single-phase and three-phase inverter systems.

MODULATION THEORY

a) Amplitude Modulation Index (M_a)

The amplitude modulation index is defined as the ratio of the peak amplitude of the sinusoidal reference signal to the peak amplitude of the triangular carrier signal.

$M_a = V_m / V_c$

Where V_m is the peak amplitude of the sinusoidal reference signal and V_c is the peak amplitude of the triangular carrier signal.

The modulation index directly controls the amplitude of the fundamental component of the inverter output voltage. In the linear modulation region ($0 \leq Ma \leq 1$), the RMS output voltage varies proportionally with Ma.

b) Fundamental output voltage:

$Vo1 = Ma \times (Vdc / 2)$

c) RMS value of the fundamental component:

$V_{o,rms} = (M_a \times V_{dc}) / (2\sqrt{2})$

When $M_a > 1$, the inverter enters the over-modulation region, where waveform distortion increases and the output approaches a square wave.

d) Frequency Modulation Ratio (Mf)

The frequency modulation ratio is defined as the ratio of carrier frequency to reference frequency.

$M_f = f_c / f_m$

A higher frequency ratio increases the number of switching pulses per cycle and shifts harmonics toward higher frequencies.

e) Harmonic frequencies are given by

$f_h = kf_c \pm nf_m$

Where k = 1,2,3... and n = 1,3,5... . These harmonics appear around multiples of the carrier frequency and can be filtered using an LC low-pass filter.

f) Relationship between Modulation Index and Output Voltage

In the linear region of SPWM, the output voltage of the inverter increases proportionally with the modulation index. Experimental observations confirm this linear relationship, making SPWM a reliable and efficient method for voltage control in single-phase inverter systems.

SYSTEM CONFIGURATION

The overall system configuration of the proposed SPWM-based single-phase inverter is designed to clearly demonstrate the flow of power and control signals from the DC source to the final AC output. The configuration integrates a digital control section with a power conversion stage to achieve efficient and controllable DC–AC conversion. As illustrated in the block diagram above, the system begins with a DC input source, which supplies power to the inverter. The SPWM control unit generates precise firing pulses based on modulation index adjustment, and these pulses are then amplified through a gate driver circuit to properly drive the power switches of the full-bridge inverter. The inverter stage converts the DC voltage into a high-frequency PWM AC waveform, which is subsequently passed through an LC output filter to remove switching harmonics and produce a smooth sinusoidal output suitable for the connected load. This structured configuration ensures coordinated operation between control and power stages, enabling accurate voltage regulation and improved waveform quality through modulation index control.

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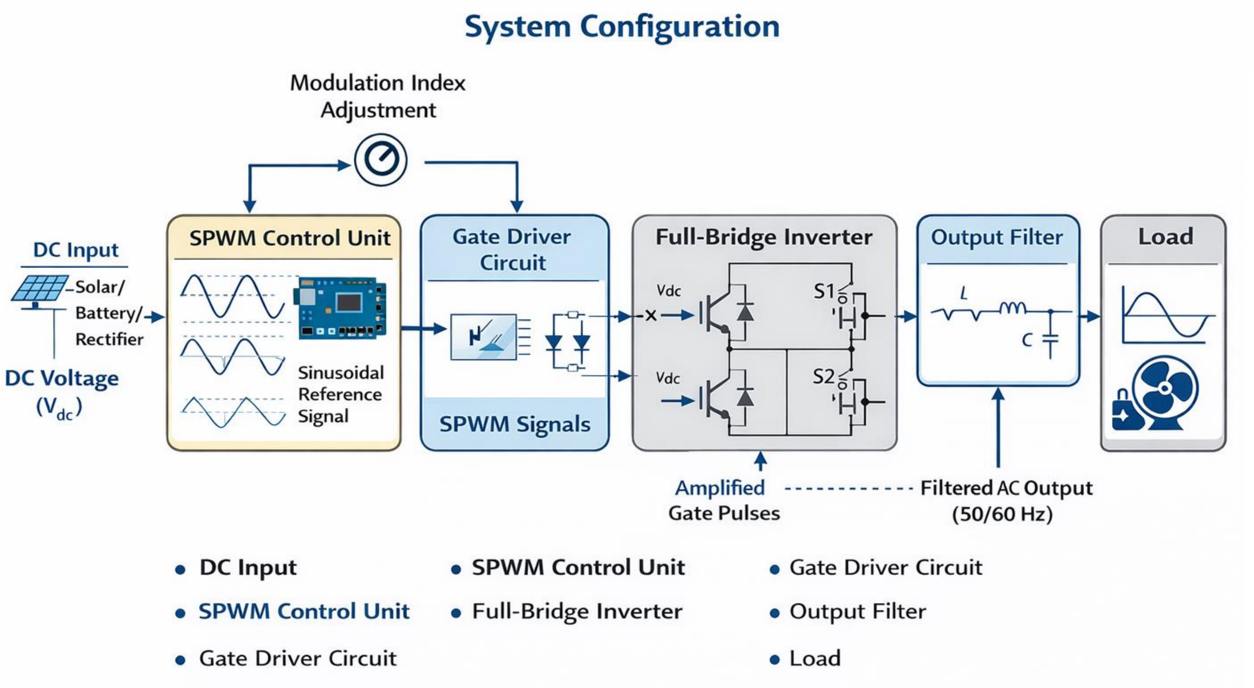

Fig.3 SPWM inverter system configuration diagram

The system is supplied with a DC source obtained from a battery, rectifier or solar photovoltaic system. This DC voltage (V_{dc}) acts as the primary energy source for the inverter. Proper filtering capacitors are used at the input to reduce ripple and ensure stable switching operation.

a) SPWM Control Unit

The control unit generates SPWM firing pulses by comparing a sinusoidal reference signal with a high-frequency triangular carrier signal. A microcontroller such as Arduino produces complementary gate pulses while maintaining proper timing to prevent shoot-through conditions. The modulation index can be adjusted to control output voltage.

b) Gate Driver Circuit

The gate driver circuit amplifies and isolates low-power microcontroller signals before applying them to MOSFET or IGBT switches. This ensures fast switching response, proper gate voltage levels and protection of the control circuitry.

c) Power Stage (Full-Bridge Inverter)

The power stage consists of four semiconductor switches arranged in an H-bridge configuration. S1 and S4 conduct during the positive half cycle while S2 and S3 conduct during the negative half cycle. SPWM pulses control the switching pattern to generate a modulated AC output.

d) Output Filter Stage

An LC low-pass filter is connected at the inverter output to remove high-frequency switching harmonics. The filter allows the fundamental frequency component to pass and produces a smooth sinusoidal waveform.

e) Load
The filtered AC output is supplied to the load, which may be resistive or inductive. The system performance is analyzed under different load conditions to observe voltage regulation and waveform quality.

FILTER DESIGN
In an SPWM-based inverter, the output voltage generated directly from the switching devices is not a pure sine wave. It contains a fundamental component along with high-frequency switching harmonics. To obtain a smooth AC output, an LC low-pass filter is used.

a) Purpose of the Output Filter:
• Remove high-frequency switching components
• Allow only the fundamental frequency (50/60 Hz) to pass
• Reduce Total Harmonic Distortion (THD)
• Improve waveform quality for sensitive loads

b) LC Low-Pass Filter Configuration:
The filter consists of a series inductor (L) and a shunt capacitor (C). The inductor resists rapid changes in current, while the capacitors smooth voltage variations.

c) Cutoff Frequency:
$f_{cutoff} = 1 / (2\pi\sqrt{(LC)})$
For effective filtering, the cutoff frequency must satisfy: $f_m < f_{cutoff} << f_c$
A properly designed LC filter reduces THD, improves waveform quality, and ensures stable inverter performance.

IMPACT OF VARIATION OF MODULATION INDEX (0 TO 1) ON OUTPUT VOLTAGE
The modulation index (Ma) controls the amplitude of the inverter output voltage in SPWM systems.
$M_a = V_m / V_c$

Table No. 1 Output Voltage with respect to Modulation Index

Modulation Index (Ma)	Output Voltage (Vout)	Remark
0.1	23V	Very low output
0.2	46V	Low voltage
0.3	69V	--
0.4	92V	--
0.5	115V	Half of rated output
0.6	138V	--
0.7	161V	--
0.8	184V	--
0.9	207V	Near rated output
0.95	219V	Close to full rated output

When Ma = 0:
The reference signal amplitude becomes zero, resulting in nearly zero fundamental output voltage.
When 0 < Ma < 1 (Linear Region):
In this region, the output voltage increases linearly with Ma. The PWM pulse width increases as Ma increases, leading to higher RMS output voltage.
Fundamental Output Voltage*:*
$Vo1 = Ma \times (Vdc / 2)$
RMS Output Voltage:
$Vo,rms = (Ma \times Vdc) / (2\sqrt{2})$
This linear relationship enables smooth and efficient voltage control without changing the DC input.
When Ma = 1:
The inverter reaches the maximum limit of the linear modulation region. The output voltage achieves its maximum sinusoidal value without distortion.
In summary, varying Ma from 0 to 1 provides proportional control of inverter output voltage while maintaining good harmonic performance.

From Table 1, it is clearly observed that the inverter output voltage increases proportionally with the modulation index within the range of 0 to 0.95. At lower values of modulation index (0.10–0.30), the output voltage remains comparatively small due to narrow PWM pulse widths. As the modulation index increases, the pulse width also increases, resulting in a steady rise in the RMS output voltage.

The data shows a nearly linear relationship between modulation index and output voltage in the linear modulation region. For example, at $M_a = 0.50$ the output voltage reaches approximately half of the rated value (115 V), and as M_a approaches 0.90–0.95, the output voltage approaches the rated value (207–219 V). This confirms the theoretical principle that the fundamental output voltage of an SPWM inverter is directly proportional to the modulation index.

Therefore, the experimental results validate that modulation index control provides smooth and effective voltage regulation without altering the DC input. The inverter operates efficiently within the linear modulation region, maintaining predictable performance and improved waveform quality.

2. RESULTS AND DISCUSSION

The experimental investigation was carried out to analyze the impact of varying the modulation index on the output voltage of the SPWM-based single-phase inverter. The results clearly demonstrate that the modulation index plays a significant role in controlling the inverter output voltage.

As the modulation index increases from 0.10 to 0.95, the output voltage increases in a nearly linear manner. At lower modulation index values (0.10–0.30), narrow PWM pulses produce a lower average output voltage. As the modulation index increases, the pulse widths become wider, resulting in a higher RMS output voltage.

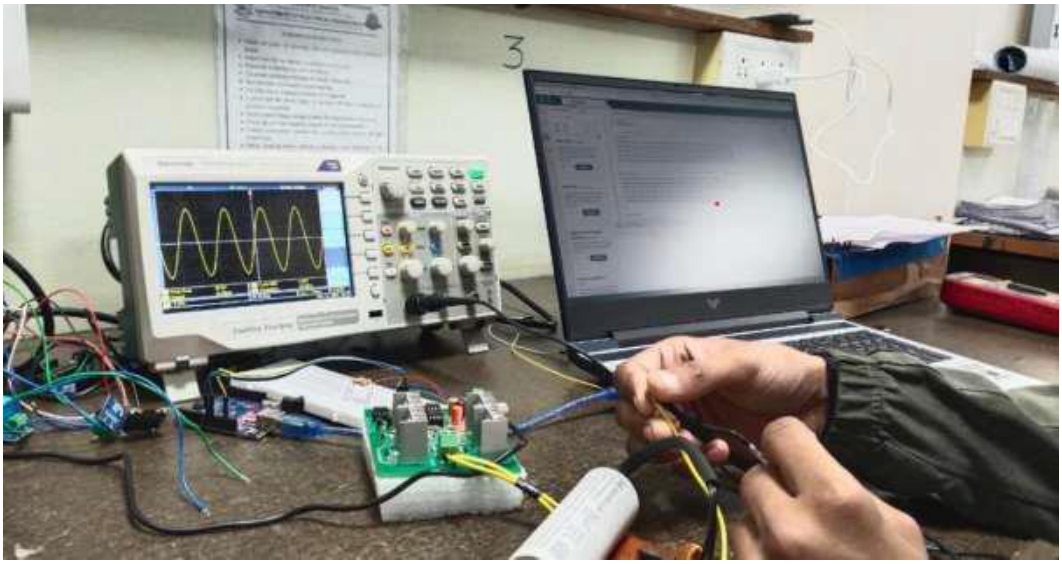

Fig.4 Hardware Setup

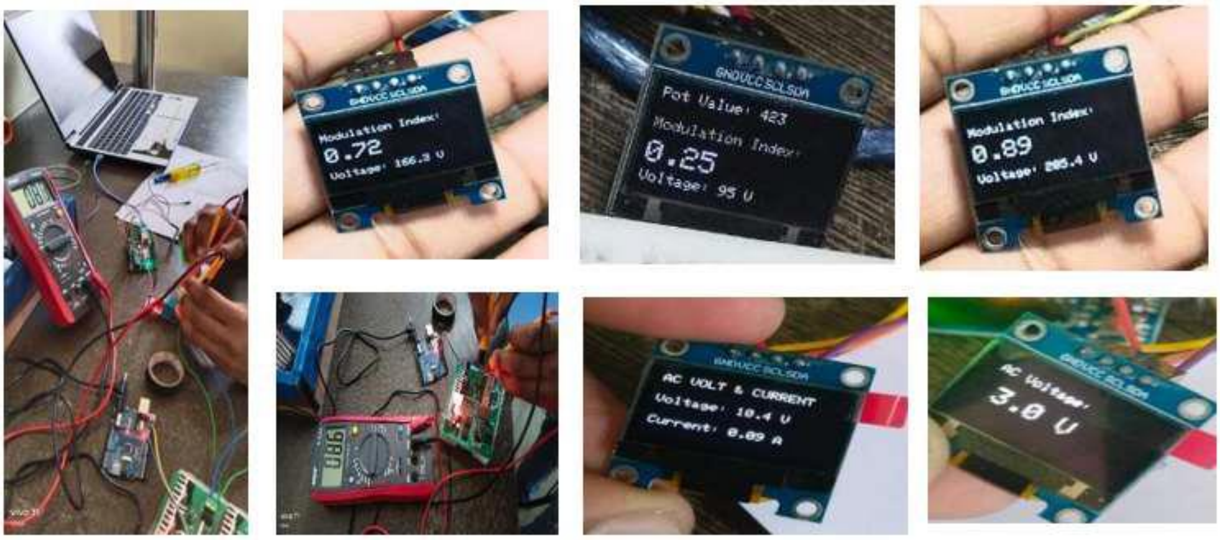

Fig.5 Hardware Setup Results

At Ma = 0.50, the output voltage reaches approximately 115 V, which is nearly half of the rated output voltage. This confirms the theoretical relationship that the fundamental output voltage is directly proportional to the modulation index within the linear region.

When the modulation index approaches 0.90–0.95, the output voltage approaches its rated value (around 207–219 V), indicating efficient utilization of the DC input supply. The inverter operates stably within the linear modulation region ($0 \leq Ma \leq 1$), and the filtered output remains smooth and sinusoidal with improved waveform quality.

3. CONCLUSION

This study successfully demonstrated the design and implementation of an SPWM-based firing pulse modulation scheme for a single-phase inverter. The experimental results confirm that the modulation index directly controls the amplitude of the inverter output voltage within the linear modulation region.

A proportional relationship between modulation index and RMS output voltage was observed, making SPWM a simple and effective technique for AC voltage regulation. By varying the modulation index from 0 to 1, smooth and predictable voltage control was achieved without changing the DC input supply. The inclusion of an LC filter ensured a nearly sinusoidal output waveform with reduced harmonic distortion.

The proposed system is suitable for educational laboratories and low-power renewable energy applications where reliable and controllable AC output is required.

4. NOMENCLATURE

V_{dc} - DC input voltage
V_m - Peak amplitude of sinusoidal reference signal
V_c - Peak amplitude of triangular carrier signal
M_a - Amplitude modulation index
M_f - Frequency modulation ratio
f_m - Fundamental (reference) frequency
f_c - Carrier (switching) frequency
V_{o1} - Fundamental component of inverter output voltage
$V_{o,rms}$ - RMS value of inverter output voltage
f_h - Harmonic frequency component
L - Output filter inductance
C - Output filter capacitance
THD - Total Harmonic Distortion
PWM - Pulse Width Modulation
SPWM - Sinusoidal Pulse Width Modulation

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